Chapter 8
Applications of TPV Generators

8.1 Introduction

8.1.1 Heat Sources

TPV systems can be classified, by the kind of reaction of the heat source, which is either a chemical reaction (rearrangement of the outer electrons of the atoms) or a nuclear reaction (rearrangement of the nucleus of the atoms). Nuclear reactions are of fusion or fission type. This classification results in three major TPV heat sources (Fig. 8.1), which are the combustion of fuels (usually hydrocarbons), solar heat and nuclear sources (radioisotopes and nuclear fission reactors). Terrestrial power generation by nuclear fusion is not considered here further, because effective exploitation seems to be decades in the future.

This book defines a fourth general heat source, waste heat, such as from industrial high-temperature processes. This heat derives mostly from fossil fuel combustion and in some cases from electrical heating, where the major purpose is the provision of process heat. The four sections in this chapter discuss nuclear, solar, combustion and waste heat source application in more detail (Sects. 8.2–8.5).

Hybrid systems consisting of a TPV system combined (not cascaded) with another energy conversion or storage device have also been of interest. Examples include TPV generators combined with a secondary battery providing high peak power [1] or combined with a renewable generator (e.g., solar PV or wind see Sect. 8.4.4) [2]. As already discussed, hybrid systems with more than one heat source (e.g., solar and combustion) are also of interest (see Sect. 8.3.2).

8.1.2 Literature of TPV Applications

In this subsection literature about potential TPV applications is reviewed in chronological order. *Ralph* et al. identified near-term and long-term applications

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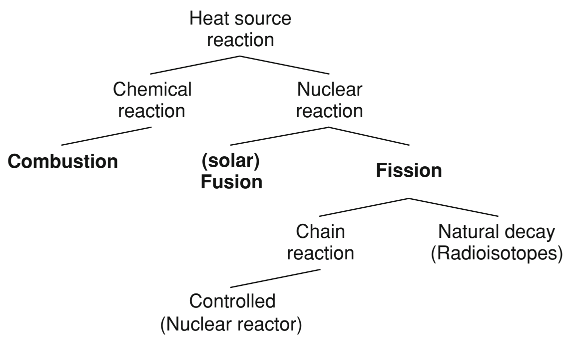


Fig. 8.1 Heat sources of TPV conversion classified by their reactions

for TPV [3]. Near-term markets were characterised by small-scale use, high price and specific TPV advantages. The identified markets were leisure power for applications such as recreational vehicles, boats and cabins (simplicity, quiet and reliable operation and prestige value), battery charges for applications such as military man-packs and portable generators (lightweight), isotope space power for applications such as deep space missions and grid-independent self-powered heaters for applications such gas furnaces and water heater. Potential long-term applications were seen in the vehicles (green car, hybrid electric and military), nuclear (submarines and space reactor) and utility sectors (off-grid, cogeneration and hybrid renewable back-up) [3].

Krist [4] listed potential TPV applications for the gas industry. Self-powered gas heating and cooling devices have been identified as the major applications, such as residential and commercial furnaces, absorption coolers, water heaters, industrial dryers and fireplace power devices (heat circulating and decorative logs). The following advantages were reported: operation during power faults, surplus electricity generation for back-up power, simpler installation (no electrical grid connection required), higher on-site gas consumption (higher gas sales) and energy conservation through on-site generation. In long-term, CHP systems with a minimum gas-to-electric efficiency of 20% and remote power systems for cathodic protection were seen as potential applications. No statement about the power range was made.

Rose [5] gave examples of potential portable TPV applications arranged by their power range: larger than watts to kW (telephones, home electronics, computers, navigational buoy and soldier systems); kW to 10 kW (tools, recreational vehicles, wheelchairs and actuation), 10 to 100 kW (yachts, remotely piloted vehicles, golf carts and electric cars) and larger than 100 kW (advanced radar, spacecraft, electric bus and weapons).

Ostrowski et al. [6] considered the user need, market value, market size, external funding and competing technologies for the assessment. Three classes of applications were identified:

- Near-term: recreational (yacht, RV units) and military.
- Medium-term: commercial (backup power) and remote power (transmitter, cathodic protection and water pumping).

- Long-term: residential (CHP), transportation (low emission fleet and hybrid), electric power (peak loading and grid extension), space mission (satellite).

Johnson [7] predicted that TPV conversion should be advantageous for applications below 5 kW and that there is strong competition above this power. The work defined a hypothetical TPV device in order to assess potential markets. The specifications were assumed as follows: variable power output of 500 to 5,000 W, an efficiency of 10% and a size of $0.6 \times 0.6 \times 0.9$ m^3 (up to 15 kW/m^3). The four application groups identified were recreational vehicles, homes without grid connection, uninterruptible power and military.

Yamaguchi et al. [8, 9] assessed the markets in the area of solar TPV, industrial high-temperature waste heat recovery, micro CHP and portable generators for the commercial Japanese market. Their work selected portable power and micro CHP as the most promising applications. The major requirements for portable generators were identified as high power density, high system efficiency, fuel flexibility, low noise and low price. Competitors (fuel cells, ICE generators, batteries) were also considered and TPV was found to have specific advantages in the power range below 5 kW (especially fuel flexibility, power density and low noise). A micro CHP TPV system with an electrical power of 1 kW and 10 to 20% gas-to-electric efficiency was also modelled in terms of cost and energy savings, where the TPV system supplied the total heat demand using a thermal storage system [8, 9].

Bard presented five major application fields [10]. As an example repeater station for telecommunication was discussed. There are about 6,000 off-grid units with a power of around 50 W in Germany. He discussed costs of a solar PV-battery system and showed that a hybrid system consisting of solar PV, battery and TPV combustion generator could result in more cost-effective solutions. Thermoelectric and DMFC systems were the major competing technologies. The following other application fields were proposed:

- Renewable energy (solar TPV, cogeneration with biomass).
- Small power off-grid supply, <1 kW (environmental monitoring, repeater stations, portable power and backup for PV systems).
- Auxiliary power unit (especially cars, recreational vehicle, sailing boats and trucks, optionally with heat/air conditioning).
- Grid-independent heating appliances (avoidance of electrical grid connection).
- Cogeneration (residential and industrial).

Table 8.1 sums up relevant applications for several competing technologies.

8.1.3 Assumptions of the Application Assessment

At the end of this chapter, an assessment of potential civilian TPV applications is presented (Table 8.5). In the following the necessary assumptions are discussed. As already discussed in Sect. 6.5.5, cascaded systems consisting of a TPV generator and another conversion device are less advantageous. Hence, such systems

Table 8.1 Summary of applications identified from competing technologies

Technology	Applications
Internal heat engine generator (ICE) [11, 12]	Lighting, electronics (e.g., TV, filming and laptop), garden, forest and construction tools (e.g., hedge trimmer, drill, cement mixer, crane and elevator, circular saw, welding), outdoor events (e.g., music, shops), mains backup (home, medical) and auxiliary power for vehicles (e.g., ships, trucks)
Stirling engine generator [13]	Artificial heart power, underwater power unit, space power, remote power sources, military ground power, solar thermal generator and CHP
Battery[14]	Entertainment (lighting, toys and games, photography), vehicle (starting, lighting, ignition, electric/hybrid propulsion, mining, recreational, personal mobility), personal communications devices (portable computers), power tools and backup power (telecommunications, industrial, utility-related)
Fuel cell [15, 16]	1–10 W: camcorder, micro-satellite, palm-top computer, safety lamps and flashlights
	10–100 W: battery re-charger, hand-held power tool, mobile/variable road sign, outdoor/camping supply, portable PC, radio communication and surveillance camera
	100–500 W: domestic gardening equipment, domestic power supply backup, heavy duty battery re-charging, professional power tools and telecommunication field equipment
	1 kW–1 MW: distributed generation (optionally with CHP)
	10–200 kW: road vehicle
	1–10 kW: auxiliary power units (APUs) for vehicles
	Space (satellite) and military (submarine)
Thermoelectric generator [17, 18]	Oil and gas (cathodic protection, supervisory control and data acquisition, offshore), telecom use (relay station, military communication and emergency services), self-powered heating devices, power from vehicle exhaust, power from waste heat
Thermionic generator [19]	Space solar systems (30 to 70 kW), space nuclear reactor (20 kW–MW), terrestrial applications had little attention over the last two decades
Alkali metal thermal-to-electric converter (AMTEC) [20]	Hybrid electric vehicle, portable power (military, battery charger), micro CHP, remote power (lighting, residential), utility power, recreational vehicle, air conditioning power, self-powered furnaces and radioisotope space power
Solar PV [21]	Utility power, recreational vehicles (e.g., boats), remote housing, forest and parks, military, telecommunication, oil and gas (cathodic protection), highway, railroad and marine, agriculture, outdoor lights, refrigerators, computers, lighting, monitoring and instrumentation, remote weather stations, telemetry systems, navigational aids and water pumping

Table 8.2 Summary of efficiency assumptions for the applications assessment. The table shows from left to right the combustion efficiency and the combustion CHP efficiency, as well as the solar, radioisotope and waste heat electrical and CHP efficiency

	Fuel-to-electricity conversion (combustion)		Heat-to-electricity conversion (solar, waste heat, radioisotope)	
	η_{sys} (%)	$\eta_{sys,CHP}$ (%)	η_{TPV} (%)	$\eta_{TPV,CHP}$ (%)
(System cost reduction)	<5	80	<6	100
Demonstrated	5	80	6	100
Near-term	10	80	13	100
Medium-term	15	80	19	100
Long-term	20	80	25	100
(Excluded)	>20	80	>25	100

have not been considered. In the assessment, space and military applications, as well as applications using nuclear sources are briefly discussed to give a comprehensive overview, but have been not discussed in depth, since this book focuses on the commercial and industrial sectors. Only radioisotope generators for space have been included, since this application seems particularly promising. The methodology was to identify first a target power and a target efficiency range. Afterwards the applications are compared by a rating system with four indicators.

The target *power range* of the applications has been expressed on a logarithmic scale in steps of ten. The smallest electrical power currently under consideration for TPV micro generators is in the mW range (see Sect. 6.5.3). A standard upper power range limit of 10 kW has been assumed because competing technologies above this power have high efficiencies (larger than 20%). Also, currently PV cells for TPV systems are only available in limited quantities at high costs. In addition, the maximum demonstrated power of a TPV system has been in the kW range. The absolute upper power range limit has been extended up to 1 MW, if TPV conversion is found to have unique advantages over its competitors. This power range definitions have lead to the exclusion of applications with an electrical power above 1 MW (e.g., centralised power stations).

Efficiency is usually defined as the ratio of the useful output to the total input. The useful output has been assumed either as electricity, or as heat and electricity (CHP mode). Two input modes have been assumed, which were either the product of calorific value and flow rate for a combustion system or a heat flux for all other sources (waste heat, solar and radioisotope). This resulted in four efficiency groups (Table 8.2).

The combustion system efficiencies of around $\eta_{sys} = 8\%$ have been reported [22, 23]. In this work a demonstrated value $\eta_{sys} = 5\%$ has been assumed taking some housekeeping power into account and making cautious assumptions. Applications with lower efficiencies than 5% should allow simple system design at reduced costs. Efficiency targets of 10% (near-term), 15% (medium-term) and 20% (long-term) have been assumed. The medium-term efficiency target has been considered as a standard upper limit for the selected applications. The CHP combustion efficiency has been generally assumed with $\eta_{sys,CHP} = 80\%$ [24].

For waste heat, radioisotope and solar applications, the efficiencies have been derived from the combustion efficiencies by excluding the 20% flue gas loss (combustion efficiencies divided by 80%). Furthermore, it has been assumed that cavity losses and all heat output from the PV cell can contribute to the useful heat output. This can be seen on the CHP efficiency with a value of 100% in Table 8.2 (see also Fig. 1.2). Applications with efficiency requirements higher than the long-term efficiency target ($\eta_{sys} > 20\%$, $\eta_{TPV} > 25\%$) have been excluded from the assessment (e.g., series hybrid electric vehicles, CHP plants above 100 kW power and centralised power stations).

Four *indicator* groups have been identified in this iterative assessment. For each indicator group specific questions have been raised and a rating from 0 to 3 has been introduced. Applications with a 0 rating have been excluded in the iterative assessment. The considered ratings were 1 (negative), 2 (balanced) and 3 (positive).

The first indicator group questions the TPV technology constraints prohibiting the use and the *research and development effort* for a specific application. Three ratings have been defined: negative (1), balanced (2) and positive (3). Factors contributing to a negative rating have been: no TPV system development, complex overall design, operation under part load, operation in a hostile environment (e.g., temperature, humidity or vibration) and high efficiency requirements (15–20%). Positive factors have been: TPV system development of at least one institution, operation partly demonstrated, efficiencies smaller than 5% sufficient and simple overall design.

The second indicator group assesses the benefit of TPV compared to *competing technologies* in a deployed (current technology) or emerging state (likely future technology). The following rating has been used:

0. TPV has disadvantages over one or more other deployed technology.
1. The disadvantages and advantages of TPV and competing deployed technologies are balanced.
2. TPV has advantages over *either* competing deployed *or* emerging technologies.
3. TPV has advantages over competing deployed *and* emerging technologies.

The following factors have been regarded as important for this indicator:

- Noise.
- Reliability, maintenance, dormancy and lifetime.
- Modularity and scalability.
- Efficiency, power density (W/m^3, W/kg).
- Heat source consideration (e.g., fuel storage or flexibility).
- Direct or alternating current power requirements.

The third indicator group *market and cost* has been rated negative (1), balanced (2) or positive (3). The following aspects have been taken into account and each individual positive, balanced or negative rating has been summed up to the overall rating:

- Three is a large potential market and a niche market. The niche market allows for higher costs to launch TPV.
- There is interest from the TPV community (market push).
- There is a market requirement (market pull).
- Long operation hours allow cost-effective operation.
- TPV system costs could match the application.
- Public funding has been available or is seen feasible.

The *human impact* is the fourth indicator. Special attention has been paid to potential primary energy savings (or global CO_2 reductions), but also local human impact factors have been considered. Local factors include low pollution (SO_x and NO_x), low noise, security of supply improvements and user friendliness (e.g., low maintenance). The following rating has been used:

0. TPV operation makes the current human impact worse.
1. TPV operation makes the current human impact neither worse nor better.
2. TPV operation could improve *either* global *or* local human impact factors.
3. TPV operation could improve both global *and* local human impact factors.

8.2 Nuclear Generator

8.2.1 Nuclear Heat Source

Two nuclear fission sources have been of interest for TPV conversion, namely nuclear reactors [25, 26] and isotopes with half-life periods shorter than the naturally occurring isotopes [24, 27–33]. One of the major attractions of nuclear sources is their high gravimetric energy density (MJ/kg) [34–37]. This results in long refuelling periods and makes them attractive for remote area supply (e.g., naval and space). Drawbacks are usually high costs and safety aspects, such as fuel processing and transport, operation, decommissioning, waste disposal and weapon capability. *Radioisotope systems* have been used as long-term source for space, remote area and pacemaker power supply with a wide heat range from mW to kW. Potentially there are over 1,300 radioisotopes [36]. For generators, most commonly Plutonium 238 and Strontium 90 are used. Plutonium 238 has a long half-life of 87 years. Hence, it is preferred for space missions, although it is more costly. The cheaper Strontium 90 with a half-life of 28 years has been used by the former Soviet Union to power remote generators along the coastline [38]. The first publications for TPV nuclear space research date back to the 1980s. Radioisotope temperatures from 1,000 to 1,200°C have been reported in TPV literature [24, 27–33], where the standard Plutonium 238 source defines the upper temperature limit.

The minimum size of a *nuclear reactor* is limited by the critical mass of the fissionable material used. The smallest reactors developed for space exploration had a thermal power in the order of tens of kW heat [35]. At the upper end of the

power range are civilian nuclear power stations with GWs of heat. In the reactors, a coolant removes the fission heat. Coolant media include (heavy) water, gases (e.g., helium or carbon dioxide), molten salts and molten metals (e.g., sodium or lead). In a TPV system the coolant would circulate and transport heat from the reactor to the radiator, where molten metal and gas coolants have been proposed for TPV conversion [25, 26]. Gas cooled reactors, such as the currently developmental Pellet Bed Reactors are predicted to achieve radiator temperatures as high as 1,800 K [25].

8.2.2 Nuclear Applications

The major requirements for *space* applications are high reliabilities and the survivability in the space environment, as well as high power densities and high conversion efficiencies. The latter two requirements result in lower launch costs. The only long-duration heat sources are solar and nuclear sources [39], and this is where TPV systems have been considered among other conversion technologies. In unsuitable illumination conditions for PV cells (e.g., near sun and deep space) nuclear sources are used. *Nuclear reactors* for space are considered in a heat range from 10 kW to MWs [19, 35]. Competing conversion technologies include Stirling engine [13], thermionic [19] and thermoelectric generators [35]. TPV space nuclear reactor systems have been proposed but not examined in detail [3, 25].

The major TPV space research focuses on *radioisotope* systems [27–33]. Currently space radioisotope systems utilise thermoelectric converters and for future missions AMTEC, Stirling engine and TPV generators have been considered [20, 40]. TPV radioisotope system efficiencies above 20% are currently projected [24]. TPV systems have the disadvantage of a low heat sink (or PV cell) temperature. This requires large fins to cool the cells in space, or alternatively, operation of the cell at higher temperatures.

The indicator for *technology constraints* and the research and development effort has been rated as negative (Rating 1). Negative aspects were the cell cooling in space by radiation fins, operation in a hostile environment and high efficiency requirements. In terms of *competing technologies*, it has been assumed that radioisotope TPV generator in space would have advantages over competing deployed (thermoelectric generators) and emerging technologies (Stirling, AMTEC). TPV generators could be more efficient than currently used thermoelectric generators. Critical parameters are efficiency and power density (W/kg). Both, TPV and Stirling systems could achieve similar efficiencies, but a TPV system could have a higher power density. A detailed comparison can be found in the literature [41]. Hence, TPV generators should have advantages over both, deployed and emerging technologies (Rating 3). The *market and cost* indicator has been rated positive (Rating 3). The system development aims for a high value niche application with a market push and pull. Other aspects have also resulted in a positive rating, namely the long operation hours, the acceptable system costs and

availability of the funding. The replacement of radioisotope thermoelectric generators in space would not result in a major change of the *human impact*. Hence, the human impact has been rated as neither better nor worse (Rating 1).

Terrestrial centralised *nuclear reactor* power stations would require large-sized TPV generators compared to the currently small-sized research generators. Smaller nuclear generators can be found for naval (submarines and aircraft carriers) and remote applications (e.g., repeater station and navigation aids). In the smaller power range Stirling engine generators have been utilised for heat-to-electricity conversion [13]. There are also a few niche-markets for *terrestrial radioisotope* generators, where neither batteries nor combustion systems have sufficient operation times. Examples include very remote power supply (e.g., Polar region) and artificial heart power. These applications differ in their temperature level. For high temperatures, TPV systems are suitable and they would compete with Stirling engine and thermoelectric generators [13].

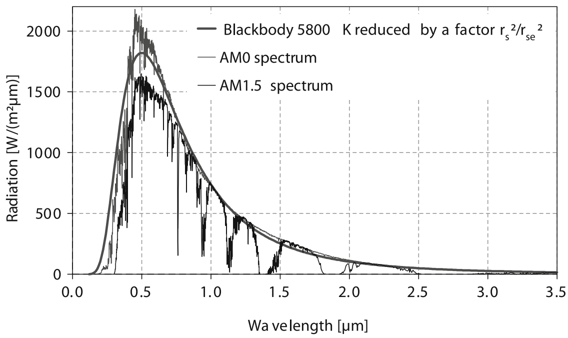
8.3 Solar Generator

8.3.1 Solar Heat Source

The nuclear fusion in the sun is a powerful and durable heat source. The sun radiates approximately as a blackbody sphere with the radius $r_s = 696 \times 10^6$ m and the temperature $T_s = 5{,}800$ K. The power emitted by the sun is approximately given by $4\pi r_s^2\,\sigma T_s^4$ with a value of approximately 4×10^{26} W, where $4\pi r_s^2$ is the sun surface area and σT_s^4 the Stefan-Boltzmann law. The incident power on the earth is about 2×10^{17} W [42, 43]. This can be compared with the average world primary power demand of around 1×10^{13} W. These values show that conversion of a small share of solar radiation on the earth would be sufficient to meet the world's energy needs. The total solar radiation intensity outside the atmosphere of the earth can be approximately calculated by the equation $r_s^2/r_{se}^2 \sigma T_s^4$, where $r_{se} = 150 \times 10^9$ m is the sun-earth distance and $T_s = 5{,}800$ K is the blackbody temperature. The total value is 1,380 W/m^2 and Fig. 8.2 shows the spectral dependence of the solar radiation. The figure also compares the 5,800 K blackbody spectrum with the standardised AM0 spectrum outside the Earth's atmosphere. It can be seen that the 5,800 K blackbody spectrum closely matches the AM0 spectrum. As solar radiation passes through the atmosphere, it is attenuated by scattering and absorption. The air mass (AM), is the path length through Earth's atmosphere for the solar radiation. Figure 8.2 also shows the terrestrial AM1.5 radiation spectrum [44, 45].

Compared to other heat sources (e.g., combustion and nuclear), the solar source has advantages such as cost-free availability, no pollution and no weight gain through the heat source. The major drawback of the sun as a heat source is the unsteady availability and the low intensity. The incident solar radiation on a surface varies in terms of its spectrum, angle and total intensity depending on factors such as location (e.g., latitude), orientation (e.g., tilt), operation

Fig. 8.2 AM0 and AM1.5 solar spectra and 5800 K blackbody radiation at sun-earth distance



environment (e.g., reflected indirect radiation), cloud cover and different cycles (sun, annual, seasonal and daily). At optimum condition (no clouds and optimum tilt angle) the intensity of the terrestrial solar radiation is about 0.1 W/cm^2. The low intensity of solar radiation requires solar concentration in order to achieve suitable radiator temperatures for TPV (>1,000°C).

The principle of *solar concentration* to increase the temperature has long been known (e.g., Archimedes). More recently, solar concentrators have also been extensively used for thermal and electrical systems [46]. In future, solar thermal power plants are predicted to contribute considerably to the electricity supply. A key advantage of these plants is the storage of thermal energy, because heat storage is more economical compared to electrical storage. The same argument can be brought forwards for TPV systems, which could also utilise a high-temperature storage. In general, solar concentrators require locations with a high share of direct sunlight, whereas, locations with a high share of diffuse radiation, are usually not suitable. Concentrating solar systems in high direct insolation areas (e.g., Southern Europe) could supply low insolation areas with diffuse radiation (e.g., Northern Europe) via long distance electric power transmission (e.g., high-voltage direct current lines) [47]. In this way, also low insolation areas could be supplied by solar concentrating systems. Solar concentrators are devices that focus the solar radiation from a large aperture area A_a onto a smaller receiver area A_r facing the sun. Equation 8.1 defines the maximum concentration A_a/A_r, where the sun-earth distance is $r_{se} = 150 \times 10^9$ m, the sun radius is $r_s = 696 \times 10^6\ m$, n is the refractive index and θ_s is the opening half angle of the sun at the Earth's surface. It can be seen that dielectric materials can increase the concentration by a factor n^2. This requires a design with optically coupled absorber and dielectric concentrator [48, 49].

$$\left(\frac{A_a}{A_r}\right)_{max} = \frac{r_{se}^2}{r_s^2} n^2 = \frac{n^2}{\sin^2 \theta_s} = 46448 \cdot n^2 \tag{8.1}$$

The blackbody temperature of the sun surface defines the upper limit of the absorber temperature with a value of about 5,800 K [42]. Experiments demonstrated absorber temperatures as high as 3,000°C [46]. The thermodynamic limit of solar TPV conversion depending on the absorber temperature T_a is given by

Eq. 8.2, where a maximum of 85% at an absorber temperature of 2,478 K occurs, assuming $T_s = 5{,}800$ K and $T_c = 300$ K. It has to be pointed out that this efficiency can be slightly exceeded if the absorber is not a blackbody [42, 50]. It can be also pointed out that the efficiency depends only weakly on T_a at this maximum. Hence, high efficiencies with lower absorber temperatures are feasible.

$$\eta = \left[1 - \left(\frac{T_a}{T_s}\right)^4\right]\left(1 - \frac{T_c}{T_a}\right) \tag{8.2}$$

Solar *concentrator types* can be broadly classified into three categories: non-tracking, single-axis tracking (line focus systems) and two-axis tracking (point-focus systems). For TPV conversion, point-focus systems with a higher concentration achieve suitably high absorber temperatures. TPV work has been reported on dish concentrators [51–55] and a Fresnel point-focus concentrator [56]. Absorber temperatures in STPV systems of 1,350°C have been demonstrated [52, 55]. Concentration levels in the range from 5,000 [57] to 25,000 [58] have been reported. The restrictions in terms of the availability of the sun can be overcome in a solar TPV system by using two strategies, which may also be combined. In the first configuration, the high-temperature heat is *stored thermally* and supplied at times when less or no solar radiation is available. The second configuration is a *hybrid systems* that uses solar radiation *and* an additional heat source (usually combustion) to supply heat for times with no or low availability of solar radiation [53–55, 58–63].

Solar TPV systems have some advantages compared to those TPV systems with other heat sources. Potentially solar systems could operate at very high radiator temperatures close to the thermodynamic optimum at 2,478 K [64–66]. Also the radiator can be completely surrounded by an inert gas or vacuum and this should allow a simple system design (e.g., similar to a light bulb) without challenging high-temperature seals [64–66].

Solar TPV systems may require some additional components. For example, systems using a thermal storage would require a controlled shutter mechanism to minimise heat losses from the storage (see Sect. 2.6).

8.3.2 Solar Applications

The first publications for solar TPV *space* research date back to the 1980s. For space applications, in the majority of cases, solar power is preferred over nuclear power [40]. Applications with intermittent solar radiation (e.g., low earth orbit) usually utilise secondary batteries as electrical storages [40]. These batteries have disadvantages in terms of energy density and lifetime. Attractions of solar TPV for space include the potential of a high efficiency, a high power density and a long lifetime. Solar TPV systems using a high-temperature thermal energy storage have been proposed to replace PV cell/battery space systems [53]. A specific

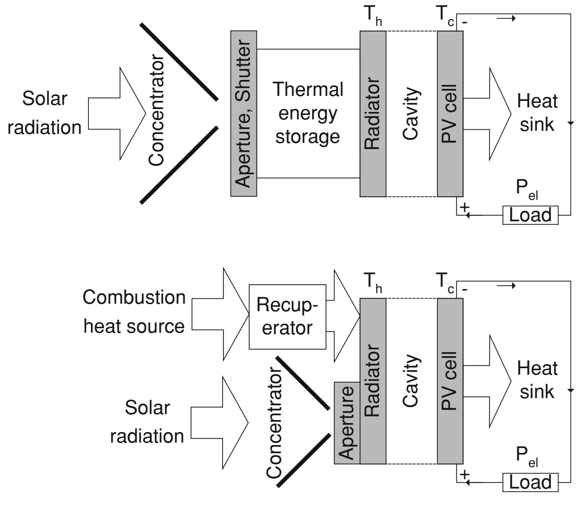


Fig. 8.3 Schematic of a solar TPV system with thermal energy storage (*top*) and a hybrid TPV solar/combustion system (*bottom*)

technological drawback is the requirement for a low PV cell operating temperature resulting in cooling challenges in space. Other technologies considered include Stirling engines and thermionic generators [19].

As discussed earlier, for *terrestrial* applications a suitable climate with a high share of direct solar radiation is usually required. Potential advantages of solar TPV include the high efficiency due to spectral control and the insensitivity to changes in the radiation spectrum, compared to solar concentrator PV systems. At the current research stage, practical solar TPV demonstrators face often difficulties in terms of high-temperature engineering. Solar concentrator systems based on both photovoltaics and Stirling generators have demonstrated high efficiencies [13, 67]. For example, a single multi-bandgap solar PV concentrator cell (GaInP/GaAs/Ge) with an efficiency of about 41% at 240 suns has been reported [68]. Potentially solar TPV systems should also achieve high efficiencies. A solar TPV system was reported that aimed for a solar-to-electric efficiency of 30% [23]. Similarly, in the European research project FULLSPECTRUM solar TPV system efficiencies in a range from 25 to 35% were predicted [69]. At the current stage demonstrated efficiencies are much lower. Also basic PV cell efficiency calculations indicate that a single-bandgap GaSb cell can currently not achieve heat-to-electric efficiencies higher than around 30% in a TPV system (Sect. 4.6.1). These considerations show that currently solar PV concentrator systems using multi-bandgap cells outperform solar TPV systems using a single-bandgap cell. In the long-term solar TPV systems with multi-bandgap cells may be competitive, but the system integration of these cells is currently in an early research stage. Hence, it can be argued that research should not focus on simple solar TPV systems but on other concepts. Solar TPV hybrid or thermal storage systems have other specific advantages compared to solar PV concentrator systems, which can make efficiency considerations secondary (Fig. 8.3).

One possibility is the design of a *hybrid solar-combustion TPV system* (Fig. 8.3 bottom) Such system has been designed using natural gas as a fuel with an electrical output power of around 500 W [23]. This system could also operate in CHP mode. Solar TPV systems using a thermal storage system have been assessed for space applications and may be also applicable for terrestrial use. Thermal storage-based systems could potentially supply heat and power continuously and autonomously with long lifetimes (e.g., no refuelling required and no moving parts). In the short-term such storage and hybrid systems could be used for non-grid connected applications. The niche market would allow for higher costs to launch TPV. Civilian applications may include remote manned (e.g., developing countries) or unmanned power supplies (e.g., relay station, data acquisition, weather stations and navigational aids). For an unsteady load such systems may require an additional electrical storage capability (e.g., secondary battery). In the long-term hybrid solar-combustion TPV systems may be utilised as grid-connected distributed CHP systems [70]. For the thermal storage or hybrid system a long lifetime and a high reliability can be expected. The distributed generation market would be generally very large. Depending on the application and the detailed system design, solar TPV hybrid or thermal storage systems could operate up to 24 h per day.

A prototype hybrid solar/natural gas TPV system has been built. Extrapolation from measurement predicted a solar-to-electricity *efficiency* of 22% and a gas-to-electricity efficiency of about 16% [23]. The project identified a large potential market in the area of grid-connected hybrid solar/natural gas TPV systems with CHP utilisation (e.g., supermarkets, hospitals, hotels, athletic clubs, food processor, restaurants). The ultimate efficiency goals were solar-to-electricity efficiency of 25% and gas-to-electricity efficiency of 20%. For remote (non-grid connected) applications, lower efficiencies could be acceptable. For example thermoelectric converters have been applied in niche market applications with low efficiencies (smaller 5%). Hence, TPV systems with gas-to-electricity efficiencies larger 5% can be regarded as competitive for some niche market applications.

In the small *power range*, hybrid or thermal storage systems could be of interest for unmanned remote applications. In remote, non-grid connected, applications the time interval of site visits and the power requirements are decisive parameters for the selection of a suitable technology (see Fig. 8.4). Flat plate PV cell/battery system or a combustion driven thermoelectric generator may also supply small power applications. Such systems are thought to be less complex compared to a TPV hybrid or thermal storage solar systems. Hence, a minimum power of 100 W can be assumed to justify the more complex hybrid solar TPV approach. Large power installations are likely to allow more maintenance and monitoring, thus permitting the use of deployed diesel engine generators. A maximum competitive power in the order of 10 kW can be assumed.

Compared to other TPV systems, solar TPV storage/combustion systems would need to overcome some additional *technology constraints* compared to simple TPV systems. They include the complex overall design, the operation in hostile environments and the operation under part load for some applications, as well as

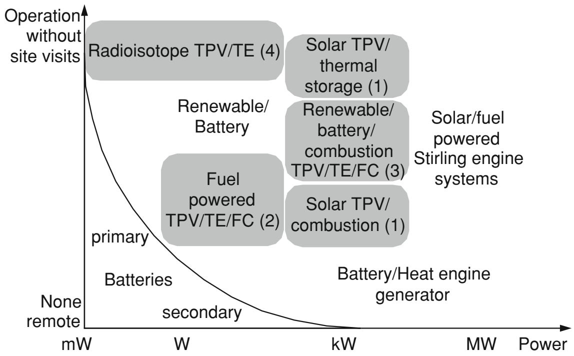


Fig. 8.4 Plot of the identified technology options for remote power supply.The dotted boxes are the areas of interest for TPV generators. The four TPV options considered are solar TPV systems with thermal storage or an additional combustion source (*1*), combustion TPV systems (*2*), combustion TPV systems combined with a battery and a renewable source such as a solar PV or a wind system (*3*) and radioisotope TPV generators (*4*). Thermoelectric generators have been abbreviated with TE, and fuel cells with FC. Applications with a low number of site visits are considered as non-remote

some fundamental work on heat transfer if a thermal storage is included (see Sect. 2.6). Overall, the technology constraints and the research and development effort were rated as negative (Rating 1).

A solar TPV hybrid or thermal storage system is likely to have advantages over both deployed and emerging *competing* technologies (Rating 3). Deployed technologies are solar PV/battery systems, diesel generators and thermoelectric generators. All of them have all their own disadvantages in terms of lifetime and costs (solar PV/secondary battery), maintenance and noise (diesel generator) or efficiency (thermoelectric generator). Another potential system may be the combination of a PV cell, an electrolyser, a hydrogen storage system and a fuel cell. Such system can be regarded as complex and costly. Fuel cell systems operating purely from a fuel tank would have high fuel requirements (large tanks and frequent site visits). Solar/combustion hybrid systems using Stirling engines have also been investigated, but are considered here to suit the power range around or above 10 kW [71].

Market and cost issues can be regarded as positive (Rating 3). There has been at least one funded TPV project [23]. In addition, this application has a potential niche market (e.g., off-grid supply) and a large potential market (distributed generation). Depending on the application and the detailed system design, solar TPV hybrid or thermal storage systems could operate up to 24 h per day. Some colder countries are less suitable, because of the high fraction of diffuse sunlight and lower solar intensity. Nevertheless, for such countries the application offers a large potential export market (e.g., countries with an unreliable or no grid). The *human impact* can be regarded as positive in terms of global and local impact factors (Rating 3).

8.4 Combustion Generator

8.4.1 Combustion Heat Source

Currently, the major part of the world's energy consumption originates from fossil fuel combustion. Combustion as a heat source for TPV conversion has been considered for a wide range of powers. Combustion systems that generate heat as small as about 1 W have been researched [72]. For small power applications, battery substitutes with a thermal power in the order of 100 W have been reported [1, 73–76]. For large power applications, CHP plants based on TPV in the order of 100 kW to 1 MW heat were considered [65, 77].

In general, combustion heat sources achieve suitable radiator *temperatures* for TPV operation (typically 1,000–1700°C). Combustion chamber temperatures depend on the type of fuel (e.g., calorific value, moisture content or aggregate state), type of oxidiser (e.g., air or oxygen), the type of flue gas heat recovery and several other factors (e.g., type of fuel-oxidiser mixing). For TPV, all major methods of flue gas heat recovery have been considered. These include air preheating using recuperator [78, 79] and regenerator devices [80–82], as well as fuel preheating [79] and flue gas recirculation using flame tubes [78, 83]. Lower calorific value fuels tend to generate radiator temperatures at the lower temperature limit of TPV operation. For example for wood powder a radiator temperature of 1,400 K has been demonstrated [65]. The combustion temperature of these fuels may be enhanced by the use of flue gas recirculation [84]. For common fuels combustion temperatures up to 2,500 K are feasible [84]. However at high temperatures, difficulties in terms of thermal engineering (e.g., heat exchanger, thermal insulation) and pollution by thermal nitrogen oxide (NO_x) must be taken into account. In order to avoid excess NO*x* formation TPV designs usually define a temperature limit. Depending on national regulations maximum temperatures in a range from 1,200 to 1,500°C are reported in the literature [65, 85–87]. Additional, usually more complex, technologies to reduce NO_x emission are available. They include NO_x filters, the replacement of air by oxygen, as well as non-premixed and heat recirculating burners.

Hydrocarbon *fuels* have high gravimetric energy density values (e.g., compared to secondary batteries) [88]. This makes them attractive for portable applications (e.g., petrol in automobiles) and they can be considered as fairly safe (e.g., cigarette lighter in the pocket) [89]. Hydrocarbon combustion has disadvantages in terms of local and global pollution. Excess local pollution including oxides of nitrogen (NO_x) and oxides of sulphur (SO_x) can cause acid rain. Globally the level of carbon dioxide (CO_2) has been found to increase due to the combustion of previously stored (fossil) fuels and the increased atmospheric CO_2 is causing climate change. On the other hand biomass fuels can be regarded as CO_2 neutral.

The most important fuel elements, in terms of heat generation, are carbon and hydrogen (hydrocarbons), which react with oxygen (usually in air) to produce CO_2 and water. For TPV, most commonly *gaseous* fuels, such as methane (or natural

Table 8.3 Approximate volumetric and gravimetric energy density of some selected fuels. Higher calorific values are given. The density of the solids does not include porosities (e.g., powder or granular fills will have lower densities). Primary and secondary batteries are also shown for comparison

Fuel/battery	Type	Density (kg/m^3)	Volumetric energy density (MJ/m^3)	Gravimetric energy density (MJ/kg)
Primary battery	Carbon zinc	2,000	400	0.2
	Alkaline	3,000	1,200	0.4
	Silver oxide	4,500	1,800	0.4
	Lithium	2,500	2,000	0.8
Secondary battery	Lead acid	2,500	250	0.1
	NiCd	3,000	300	0.1
	NiMH	3,000	600	0.2
	Li ion	2,000	1,000	0.5
Gaseous fuel	Hydrogen	0.09	13	142
	Methane	0.7	40	56
	Natural gases	0.7–0.9	33–43	41–54
	Air (for comparison)	1.3	–	–
	Propane	1.9	95	50
Liquid fuel	Oils (e.g., diesel, petrol)	790–970	33,000–42,000	42–47
	Liquefied Propane	510	25,500	50
	Methanol	790	18,200	23
Solid fuel	Coal (lignite—anthracite)	1,100–1,800	28,000–67,000	26–37
	Dry wood	400–900	8,000–18,000	~20

gas), propane or butane, have been used. Combustion of *liquid* fuels usually requires a fuel feed system (e.g., pump) and atomiser, which can make system design more complex compared to gas fuelled systems (gas system can operate solely from a pressurised tank). For military applications, portable TPV systems using logistic liquid hydrocarbon fuels (e.g., kerosene, diesel) have been designed [79, 83, 90, 91]. *Solid* fuels are often associated with sophisticated combustion techniques. Nevertheless, work at the Solar Energy Research Center (SERC) in Sweden focused on cogeneration using wood powder [65]. This fuel diversity demonstrates that, as long as the radiator achieves a suitable temperature, TPV systems can operate with any fuel.

The *chemical storage of energy in hydrocarbon fuels compared with battery system* is of interest for TPV systems using hydrocarbon combustion as a heat source. Hydrocarbon fuels are advantageous in terms of availability, long-term storage and transport characteristics. Liquid and gaseous hydrocarbon fuels share high gravimetric energy densities (Table 8.3) with values more than 100 times higher compared to secondary batteries [88]. Some gaseous fuels can be liquefied in order to achieve similar volumetric energy densities to oils (Table. 8.3) [88, 92–94].

These liquid fuels (diesel, kerosene, liquefied propane) with both high volumetric and gravimetric energy density have been utilised for portable TPV applications [83, 88, 91, 95, 96].

In the majority of cases TPV combustion systems have utilised hydrocarbon fuels, although hydrogen has also been burned in converters with small powers [73]. Hydrocarbon fuels are widely available, can be easily stored, transported and recharged. Additionally they have high gravimetric energy densities [88]. Competing technologies for hydrocarbon-powered TPV generators are mostly batteries in the smaller power range and ICE generators in the larger power range. Fuel cells are emerging for these applications and can be considered as a major competitor.

Williams et al. [76] demonstrated the *direct conversion of flame radiation* with a PV cell without using a radiator. The infrared radiation of hydrocarbon flames is composed of major spectral emission bands at around 2.7 and 4.4 μm [97, 98] and greybody radiation from carbon particles within the flame (soot) [76, 99]. The ratio of radiative heat transfer to the total heat released by the combustion depends on fuel type and burner design as well as other parameters. For natural gas this ratio can reach values as high as 30% for modern industrial burners [99] and Gaydon stated a ratio of 2–20% in an older book [100]. The flue gas can also contaminate optical elements and this can lead to degradation of the system performance. In particular dirty fuels (e.g., liquids) can cause contamination. It can be concluded that the direct conversion of flame radiation is often unsuitable for TPV conversion because of the small ratio of radiant heat to the total combustion heat, the unsuitable radiation spectrum and contamination aspects. Therefore, means to increase the radiation intensity and to tailor the spectrum are required [101]. Nevertheless, the direct conversion of flame radiation with PV cells is very illustrative to show the principle of the TPV concept.

Radiant burners have been developed for both lighting and heating applications. The historical development of spectrally selective radiant burners *for lighting* is of interest, since the mechanisms applied to enhance visible radiation for lighting can also be applied to enhance near-infrared radiation for TPV conversion. In 1826, Thomas Drummond heated a monolithic block of calcium oxide (limelight) to incandescent temperature by flame impingement using a hydrogen/oxygen flame, where the calcia block could enhance visible radiation [101]. Subsequent work focused on different radiator materials and geometries [101]. In the early 1890s, Carl Auer (Baron von Welsbach) perfected both the material compositions and the geometrical structure by using fibres of around 10 μm in diameter consisting of 99.3% of thoria (ThO_2) and 0.7% of ceria (Ce_2O_3) by weight. This structure, known as the Welsbach mantle, continues to be the most efficient converter of gas combustion heat to visible light and is still being used for example in camping lanterns [101, 102]. The Welsbach mantle is optically thick in the visible spectral range and optically thin in the infrared range (1–8 μm) [102]. For most spectral regions the combustion flame is also optically thin, except some spectral bands mainly at around 2.7 and 4.3 μm, so that the Welsbach mantle emits most radiation in the visible range where the mantle is optically thick. The physically small fibre diameters can achieve temperatures close to that of the flame and the combustion products, because their

small physical size allows high heat transfer rates. The thin fibres are tolerant to thermal stress and can be heated up quickly [101]. However scaled up Welsbach mantles have proved to be fragile [103].

Radiant burners for heating can be broadly classified into direct and indirect radiant burners. Indirect-fired burners spatially and optically separate the combustion and heating zone, whereas direct-fired burners do not separate these two zones. Alternatively, combustion processes can be classified by the premixing mode of oxidiser and fuel. Premixed burners mix oxidiser and fuel prior to the combustion, whereas non-premixed burners simultaneously mix and burn oxidiser and fuel.

Direct radiant burners may operate on flame impingement or utilise porous structures in the combustion zone. For TPV, physically small porous structures that are of interest are those that can be designed to achieve high temperatures and convert fuel efficiently into radiation.

The physically small porous structures have the advantage that they are in close contact to the flame [104]. High heat transfer rates between combustion gas and these structures are achieved. For this reason, these porous structures reach a high temperature. On the other hand, indirect radiant burners experience necessarily larger temperature gradients from the combustion gas to the radiator. For direct radiant burners, materials considered are typically *oxide type ceramics*. TPV radiant burners have been designed so as to use a modified Welsbach mantle, which consists of ytterbium and erbium oxides. Generally suitably high-temperature operation (more than 1,700 K) and highly selective spectral emission was achieved [103]. However, the modified Welsbach mantle also suffered from scaling and fragility difficulties. Hence alternative structures have been examined including composite fibres and foams. These structures can overcome the scaling and fragility issues of the Welsbach mantle but at the expense of spectral selectivity. Direct radiant burners using *metals* (e.g., wires) have been used in TPV systems. Metals are generally limited to lower temperatures due to oxidation in the flame atmosphere compared to ceramic oxides. One disadvantage of all direct radiant burners is that PV cell surfaces would be contaminated from combustion products. Hence, usually additional means are required to protect the cells. This is usually achieved using transparent shields (e.g., fused silica). No TPV work on the long-term contamination of these shields by the combustion products could be found in the literature, although impurities in these products could affect the shield transparency. Another drawback of direct radiant burners is that at least some unsuitable flame radiation is inherently in the emitted spectrum (at 2.7 and 4.3 μm). Typical PV cells cannot convert this radiation. Furthermore, an optically thin radiator used in direct radiant burners can usually not be used for other heat sources than combustion. At the moment, it seems that there is no commercially available direct radiant burner with a suitable performance for TPV conversion (high efficiency and selective spectrum).

Indirect radiant burners spatially enclose the combustion zone and have been used in TPV systems. These burners utilising gaseous hydrocarbon fuels are commercially available for space and industrial heating applications and are of metal or ceramic type. Ceramic burners are usually of interest for TPV because of their higher operation temperature. These burners typically have a tubular form in

various shapes including U, W, P, double P, A or single tube [105]. Single tube burner types include straight-through, single ended recuperative or single ended recirculating recuperative [99, 106]. For TPV the latter one made of silicon carbide (SiC) has typically been utilised. These burners were either commercially acquired [78] or custom-designed [83]. Additional coatings have been applied in order to achieve a spectrally selective emission. The various selective radiator options are discussed in Chap. 2 [104].

Another major engineering aspect is the recovery of flue gas heat to preheat the combustion air. The two conventionally accepted methods of recovering the flue gas heat are recuperation and regeneration. Regeneration, or regenerative firing, is based on cyclical firing of paired combustion systems with thermal energy storage For TPV conversion, regenerators are less suitable because they operate unsteadily and they are usually utilised for larger sized systems. Potentially, a single (steady) burner with a rotary regenerative heat exchanger could be used.

The major recuperator types are cross, parallel and counter flow. For TPV conversion typically counter flow recuperators are used and several designs have been investigated. The counter flow recuperator has different temperature zones. The recuperator in the high-temperature zone is necessarily made of ceramics such as silicon carbide and cordierite. In the low-temperature zone, simpler construction materials, such as stainless steel can be used. Using efficient recuperators about 80% of the chemical energy can be converted to radiant energy (see also energy balance in Fig. 8.2) [24]. Simulated and experimental efficiencies of an optimised counter flow heat exchangers exceeded 90% [86, 107]. Some TPV applications focus on heating rather than a high electrical efficiency. Here, the recuperator requirements are moderate or such system may not require a recuperator at all [108]. Also other arrangements are feasible. For example Qiu et al. proposed a cascaded radiant burner with two temperature zones using silicon cells at the high-temperature zone and GaSb cells at the low-temperature zone [109].

Complete TPV systems require not only the burner and PV cell converter but also several auxiliary parts. They include components for air and fuel conditioning (e.g., pumps, blowers, atomisers), as well as burner ignition and control. Portable systems require a fuel tank and components to remove the heat from the PV cell to the ambient (e.g., pumps, air heat exchanger). For example CHP systems may include a thermal storage tank for hot water. These examples show that there is a larger developmental step from a lab demonstrator to an autonomous operating system.

The following five subsections focus on different combustion applications in the areas of portable power, uninterruptible power supply (UPS), remote power, transportation and combined heat and power (CHP).

8.4.2 Combustion Application: Portable Power

TPV research and development of portable power generators included a multi-fuel (diesel, kerosene) generator with an electrical power of 500 W [79, 83, 91, 110],

a propane generator with 100–150 W [111], a portable generator with 5–20 W [112], a battery substitute with 20–25 W [1, 113] and a battery charger combined with a torch with about 1–3 W electrical power [88]. More recently the power range was extended to even lower electrical powers (see Sect. 6.5.3). Such small power systems have not been considered in this assessment because of their early research stage. Hence, the power range of interest has been defined from 1 W to 1 kW including the referred TPV concepts. Batteries are predominant in the lower power range and can be regarded superior below 1 W. Portable heat engine generators have advantages in the higher power range and can be regarded superior above 1 kW. Yamaguchi and co-workers also identified an upper limit of 1 kW [8, 9].

In the US, there has been military interest for portable power generators from the early phases of TPV research up to the time of writing [114–117]. The relevant advantages of TPV for military applications are quiet operation, high power densities, no moving parts, fuel flexibility, capability of CHP operation, tolerance to low temperature, simple start-up, excellent dormancy and direct current output [3, 6, 7, 10, 12, 13, 20, 117, 118]. Challenges were seen in the low demonstrated efficiency, the thermal signature due to the high-temperature operation, sensitivity to temperature changes (temperature control required), poor system experience, radiator ruggedness and up-scaling [117].

Yamaguchi et al. concluded that civilian portable generators are one of the most promising TPV applications [8, 9]. Portable generators with an intermediate power from 10 to 100 W (within the examined range from 1 W to 1 kW) and with a long operation time can be regarded as particularly promising because of low competition from other technologies. Example applications are battery chargers, lighting equipment, portable electronics (e.g., laptop, TV and filming), power tools (e.g., garden, agriculture, forest and construction), camping, temporary outdoor events (e.g., shops and music) and mobile road signs [5, 15, 16].

High conversion efficiencies are desirable in order to achieve long refuelling intervals. Portable hydrocarbon-powered TPV systems with efficiencies (fuel-to-electricity) of a few percent can be superior to current primary and secondary batteries in terms of the overall energy density due to the high energy densities of hydrocarbon fuels (MJ/kg, MJ/m^3) [88]. A minimum efficiency target of 5% has been assumed here, accounting for some weight of the TPV converter in addition to the fuel and assuming that improved energy densities compared to batteries are of interest.

The indicator for *technology constraints* and the research and development effort has been rated as balanced. Several institutions have, at least partly, demonstrated TPV operation for this application [79, 83, 91, 110]. However, a general-purpose generator would need to operate under various operation conditions (part load, hostile environment). Efficient part load operation could be possible using a TPV system in on/off mode and an additional secondary battery, but research on this issue is limited.

Major *competitors* are secondary batteries in the small power range and ICE generators in the large power range. ICE generators have disadvantages in terms of high maintenance, starting in the cold and noise. Major disadvantages of secondary

batteries are low lifetime, poor dormancy, slow recharging and limited capacity (or low volumetric and gravimetric energy densities). Fuel cells (emerging) have the advantage of a high efficiency and a good part load performance. On the other hand, TPV generators are predicted to be superior in terms of power density, lifetime and fuel flexibility, compared to fuel cells [8, 9]. It has been concluded that portable TPV generators have some advantages over deployed (secondary battery, ICE generator) and emerging technologies (fuel cell).

There are niche *markets* in portable power that have special requirements for low maintenance, low noise, low weight and long operation time. The entire battery market and heat engine generator market is potentially a large long-term market. In the TPV community there has been interest in military and civilian portable power generators (positive market push). There is also generally a market requirement (positive market pull), since currently secondary batteries often limit the system operation time (e.g., laptop). Funding for civilian portable generators may be regarded as unlikely, but overall market issues have been rated positive. The local *human impact* has been rated positive. Batteries can be regarded as bulky and heavy and difficult to refuel. Compared to heat engine generators, TPV generators should be less noisy and the continuous combustion is generally cleaner. Major CO_2 saving can be not expected for this market and this resulted in a negative global human impact. Hence, overall the human impact has been rated balanced.

8.4.3 Combustion Application: Uninterruptible Power Supplies

Uninterruptible power supplies (UPSs), also known as backup power or emergency power supplies, are used in sectors such as computer, communication (e.g., telephone network), domestic, military, security (e.g., banks and elevator), industry (e.g., power failure critical processes), medicine, emergency and lighting (e.g., airport) [6, 7, 11, 12, 14–16]. An industrial study shows that there is a wide power range for UPSs from below 1 kW (e.g., single computers) to above 100 kW (e.g., industrial production). UPSs for large computer suites can be even in the order of MWs [119]. TPV technology is particularly suitable for the lower power range up to 10 kW. Above this power, other technologies compete strongly with TPV. In the low power range UPSs are likely to operate within buildings and utilise batteries. Indoor operation of a hydrocarbon based TPV UPS would require usually flue gas extraction, which is assumed to be not justifiable below an electricity output of 100 W. It is assumed that the power is usually supplied from the grid and the TPV UPS covers occasional faults. After a power fault the TPV UPS could be refuelled. This operation mode is unlikely to require high TPV system efficiencies and a target range from 5 to 15% has been assumed. Costs and reliability are likely to be more important aspects.

The indicator for the *technology constraints* and the research and development effort has been rated as negative due to the complex overall design. A TPV UPS

system design would include an inverter (not required for DC systems), switches, a means to monitor the grid and a buffer battery. Also no UPS system development could be identified in the TPV community.

Competition arises from batteries in the small power range and ICE generators in the large power range, where disadvantages have been discussed previously for portable generators (see Sect. 8.4.2). For UPSs, often secondary batteries immediately provide power for several minutes and bring a standby diesel generator on the load for long-term backup [120]. Flywheels or capacitors in conjunction with heat engine generators may also be utilised as short-term electrical storage options [119]. UPSs using fuel cells are emerging. Fuel cell lifetime is not critical because of the low operation time (only during power fault). Hence, a TPV UPS system is regarded here to have advantages over deployed technologies, but limited advantages over fuel cells in this application.

In general the UPS *market* is large and growing. There are potentially niche markets for reliable, low noise and fuel flexible solid-state TPV UPSs. Some power failure critical applications make use of a redundant UPS, which may also be a market for TPV. Yet no market push from the TPV community could be identified. As a result the market and cost indicator has been rated as balanced. Regarding the local *human impact* a positive rating has been given, since local pollution and security of supply could improve. Also a TPV system could be more user-friendly (e.g., no regular checks as for heat engine generators or batteries) and operate quietly. A minor global human impact can be expected due to the short-term use.

8.4.4 Combustion Application: Remote Power

For future fuel powered *space* missions, it has been pointed out that advances in hydrogen storage need to be made to meet the requirements. TPV systems have been proposed as an alternative to fuel cells for space applications [121]. However, most TPV space research focuses on radioisotope rather than combustion systems (see Sect. 8.2.2).

For *terrestrial* remote power applications, the power density of the generator is usually uncritical, because operation is typically stationary. In the smaller power range the load has been assumed to be typically constant (e.g., telecommunication repeater), whereas in the large power range the load has been assumed to vary (e.g., non-grid connected households). The fuel for a remote TPV combustion system may be available on-site (e.g., gas and oil exploration) or supplied through regular site visits. Similar to thermoelectric on-site generators [17], it can be assumed that TPV generators operate reliably with a long lifetime. Remote generators typically have to operate under hostile environment conditions (e.g., temperature, humidity).

Figure 8.4 in Sec. 8.3.2 summarises potential options for remote power supply. Currently, primary batteries can supply low power and long operation applications

(e.g., battery powered radio temperature sensor) and secondary batteries are suitable for higher power and shorter operation applications (e.g., electric wheelchair or model-making). In less accessible applications requiring both high power and long operation, secondary batteries are typically recharged using a renewable source (e.g., solar PV and wind). Less remote applications allow refuelling of heat engine generators. These generators typically utilise a combustion process as a heat source (e.g., thermoelectric, heat engine, Stirling and TPV), except for fuel cells with a direct conversion. Thermoelectric generators can be advantageous in application with the following factors in their favour: fuel is on-site (e.g., gas and oil exploration), limited availability of renewable sources, high reliability requirement or long lifetime need. TPV generators promise higher efficiencies than thermoelectric generators in this niche market. Hence, the replacement of these thermoelectric generators is considered here as one potential remote TPV application and named *unmanned remote power* (Fig. 8.4, No. 2).

Very remote applications (e.g., in polar regions, deep sea or space) may have limited renewable sources and no fuel on-site. Also battery lifetime may be too short and regular refuelling may be unfeasible. In such applications radioisotope sources may be utilised together with a thermoelectric or TPV generator (Fig. 8.4, No. 4, see Sect. 8.2.2).

Another remote system option with long autonomous operation is a solar TPV system with thermal energy storage (Fig. 8.4, No. 1). Such system is not limited by battery lifetime and the (stored) heat can be converted into electricity by direct heat-to-electricity devices (e.g., TPV) or external heat engine generators (e.g., Stirling). Stirling engines are assumed to be suitable around and above the 10 kW power range. For smaller systems it can be assumed that these generators show disadvantages in terms of the complexity compared to TPV. Also the Stirling engine efficiency decreases for the smaller power range (see Sect. 7.2.2). Heat engine generators are readily available for less remote applications (Fig. 8.4, bottom right), where regular maintenance is not critical. In the intermediate power range centred around 1 kW two TPV system configurations have been identified. The first configuration is solar TPV conversion (Fig. 8.4, No. 1), which is discussed in more detail in the Sect. 8.3.2.

The third configuration (Fig. 8.4, No. 3) consists of a renewable generator (e.g., solar PV and wind) combined with a secondary battery and a combustion driven generator (e.g., TE and TPV). This configuration has the advantage, that both the renewable output power and the battery capacity can be scaled down considerably, when compared to the renewable/secondary battery configuration only. In this case, the combustion generator acts as a backup power supply if the renewable source is not available. It follows a detailed discussion of the two identified options, namely unmanned remote power (No. 2) and remote renewable-TPV hybrid system (No. 3).

Applications of *unmanned remote power* include the areas of water supply (e.g., monitoring and pumping), oil/gas exploration and distribution (e.g., cathodic protection, valve operation and data acquisition), stationary telecommunication (e.g., repeater), environmental monitoring (e.g., weather, air quality and scientific

measuring) and navigational aids (e.g., aircraft, shipping, road and rail signalling) [4–6, 15, 16, 18]. These applications have typically a constant load. The reliability requirements depend on the specific application. A large share of these applications can be supplied by a hybrid system consisting of a renewable generator and secondary batteries. There are, however, applications supplied by combustion thermoelectric generators and these would be also the niche applications of interest for TPV.

The *power range* has been identified from approximately 1 W to 1 kW using competing technology literature [13, 16, 17]. The thermoelectric generator is the major direct competitor for this small niche market. Hence the minimum efficiency has been assumed with the same value of 3% as current combustion-powered thermoelectric generator (Sect. 7.4.1). Systems with such low efficiency may be used where the fuel is cheaply available on-site, such as for oil/gas exploration and distribution. The near-term target of 10% has been selected as an upper efficiency limit. This value would be about a 3 times improvement over the efficiency of current thermoelectric generators and this may also open new markets.

The indicator for the *technology constraints* and the research and development effort has been assessed as negative. The low efficiency requirements have been regarded positive. However, negative aspects have been identified as dominating. No TPV systems development for this application could be identified and the operation in hostile environments also contributed negatively. Overall the *competition* and benefit has been rated positive compared to deployed and emerging competitors. TPV systems have demonstrated higher efficiency than thermoelectric systems (deployed). Fuel cells have demonstrated higher efficiencies than TPV, but other TPV advantages are believed to outweigh fuel cells. They include fuel flexibility and storage, as well as the potentially higher lifetime of TPV. *Market* and cost issues have been rated balanced. The TPV community identified the unmanned remote power as a niche market [6], but no work towards a system development could be identified. Another constraint is likely to be the lack of funding of this application. Potential advantages are long operating hours and the allowance for premium capital costs in this market. Portable generators and uninterruptible power supplies may be seen as a similar and potentially large market. No major improvements in terms of the *human impact* can be expected by using TPV instead of a thermoelectric generator in this application. Hence, the human impact of unmanned remote generators has been rated as neither better nor worse.

Another interesting configuration is a *remote renewable-TPV hybrid system* (Fig. 8.4 No. 3)A major drawback of renewable sources (e.g., solar PV, wind and hydro) is the fluctuation in output power (e.g., daily and seasonally). Hence, using a combined renewable and secondary battery system for non-grid connected supply requires large sizing of both secondary batteries and renewable sources to meet variation in supply and demand at all times. A possible solution to this is the use of an additional combustion-powered generator. It has been simulated that the size of the PV system can be reduced to a third of that required for an exclusively PV-based system, if only 10% of the annual demand is met by the combustion generator, assuming a constant load and Central Europe climate. It has been

pointed out that this redundancy arrangement can also improve the overall reliability [2].

For the combustion TPV generator, a target power range from 100 W to 10 kW has been assumed. The renewable generator would usually be larger than the TPV generator. Below this power range the complexity of this renewable hybrid system can be regarded as a hindrance in terms of the number of components, optimisation of the size of each component and the energy management. Above 10 kW power major competition arises from heat engine generators (e.g., ICE and Stirling). The hybrid remote power applications may be similar as those for the unmanned remote generator discussed previously. In addition to these unmanned applications, larger power applications could include remote housing (e.g., developing world) or larger telecommunications installations. Varying load demand could be met by a secondary battery. It is also feasible that the combustion TPV system would operate with on-site fuel (e.g., biomass). For fuel cell systems biomass operation is not possible in a simple way.

For the hybrid remote power system an efficiency range with a higher upper limit of 5 to 15% has been adopted, compared to the previously discussed unmanned remote application. It is believed that the higher power range makes the number of site visits for refuelling and fuel costs more important issues.

The complexity of this approach has led to a negative rating of the indicator for *technology constraints* and the research and development effort. Although TPV has been suggested for this application [2], no system development could be identified. The *competition* has been rated as advantageous and is generally regarded as similar to the previously discussed application on unmanned remote power. *Market* and cost issues have been rated as balanced and are also regarded similar to the previous application, where differences should be a shorter operation time (negative) and a larger market (positive). Currently, supplementary combustion generators are likely to be ICE based. Hence a TPV system could improve local *human impact* factors (e.g., reduced pollution due to continuous combustion, lower noise and lower maintenance). Potentially primary energy savings are feasible in the developing world using this configuration. Hence, the highest rating for the human impact has been given.

8.4.5 Combustion Application: Transport Sector

At the time of writing, the transport sector accounts for roughly one quarter of the total primary energy consumption in typical industrial countries. One major route to reduce energy consumption in this sector is the improvement of the poor energy efficiency. For example an automobile engine converts typically not more than 30% (Otto engine) to 40% (Diesel engine) from the fuel energy into useful work (maximum brake thermal efficiency) [122]. These values are for optimum load conditions and decrease further for normal operating conditions. *Battery and hybrid electric automobiles* are considered a major technology option in order to

improve this propulsion efficiency. TPV generators in the power range from 6 to 10 kW have been examined for series hybrid automobiles in the US [123, 124] and within a project funded by the EU (ΓÇ£The REVΓÇø) [125]. Potentially, a TPV generator could have advantages in terms of noise, fuel flexibility, power density, reliability and maintenance, when compared to internal combustion generators and fuel cells. The major challenge for TPV generators in hybrid vehicles is the high efficiency requirement. For example in the EU project the fuel-to-electric efficiency target has been set to 35% [125]. This value can be considered as a long-term target for TPV conversion and would require some technological progress.

Harvesting and conversion of exhaust gas energy into electricity could also improve propulsion efficiency, since electricity is typically generated from the shaft power of the propulsion engine. Thermoelectric generators are considered as a major option to convert the energy from the heat engine exhaust gas into electricity [18, 126]. A TPV system has been designed to convert exhaust gas from a gas turbine into electricity. Here, problems have been reported to meet the desired radiator temperature of around 1,300°C [127]. Automobile flue gas temperatures vary up to a maximum of around 1,000°C [126]. It can be concluded that exhaust gas power harvesting may be of interest in future, if advances in TPV conversion towards lower radiator temperature systems are made (e.g., micron-gap systems or efficient filter concepts). For this assessment exhaust gas power harvesting has been excluded because temperatures are typically too low.

The two applications considered in detail are *small power propulsions* and *auxiliary power units*. In general, the component and system requirements in the transport sector are challenging. There is a need for reliable operation in hostile environments (e.g., temperature, humidity and vibrations), as well as requirements for low weight and low maintenance.

Small vehicles in the road, air and water sector can have special requirements in terms of low noise, high reliability or low complexity. A TPV generator could meet these needs and is considered competitive in the smaller power range. Examples include the following [3, 5, 14, 128, 129]:

- Land (e.g., electric wheelchair, electric bike/trike, power assisted bicycle, luggage/pallet trolley, electric cart, recreational vehicle, sweeper, scooter, golf cart, forklift, lawnmower, snowmobile, all terrain vehicle, airport vehicle, station car, robot and remotely piloted vehicle).
- Air (e.g., small aeroplane and unmanned aeroplane).
- Water (e.g., small ship, jet-ski and unmanned submarine).

Currently either secondary batteries together with an electric motor or ICEs typically power these vehicles. Heat engines tend to be used in the larger power range and batteries in the smaller power range. In the intermediate power range, assumed here from 100 W to 10 kW, both concepts have their weaknesses. The battery concept tends to have disadvantages in terms of energy density (weight, operation range), recharging (or refuelling), low temperature operation and lifetime. On the other hand, the heat engine concept has drawbacks in terms of noise, maintenance, local pollution and starting reliability. Hence it is assumed that

combustion TPV generators together with electric motors for propulsion could have advantages compared to both existing concepts. Optionally a secondary battery may be applied to supply peak propulsion demand and to store recovered brake energy. In general high TPV conversion efficiencies are required, since high efficiencies reduce fuel to be transported and this results in a long operation time. The electric propulsion motor and possibly a battery will add additional weight. Hence, the efficiency target range has been set to the highest range of this assessment (15–20%).

The *technology constraints* and the research and development effort of this application are generally challenging. No TPV system development could be identified specifically designed for small propulsion power and there are high efficiency requirements. Other negative aspects are complex overall design requirement (energy management, battery and power electronics) and the operation in changing environmental conditions. As already discussed TPV should have specific advantages over deployed *competing* technologies (batteries and heat engines). Fuel cells are identified as the major emerging competitor. It has been assumed that TPV advantages (fuel storage and flexibility and high power density) outweigh the high efficiency of fuel cells. The largely diverse *market* should have niche applications allowing for higher costs and large potential markets at lower costs. Negative market aspects are seen to prevail and they include minor TPV community interest, the short operation time and the unlikelihood of funding. Hence a negative rating has been given. The local *human impact* has been seen as positive. Currently reciprocating heat engines are noisy and polluting (TPV uses continuous combustion) and batteries can be regarded as not user-friendly (recharging, limited operation range, safety). On the other hand, large energy saving can be regarded as unfeasible in this niche market application.

In the transport sector there is a large variety of auxiliary (non-propulsion) power consumers for comfort, safety and control functions. Here *auxiliary power units* (APUs) are of interest. The electricity is utilised for applications such as ignition, lights, starters, navigation devices, electric windlasses, alarm system control, fans, heated windows, TV, Radio and by-wire technologies (e.g., fly-by-wire, break-by-wire and steer-by-wire) [3, 6, 12, 14, 116]. The electricity required for these applications may be generated coupled or decoupled from the propulsion engine.

Typically *coupled* systems use a generator and the shaft power of the propulsion heat engine. This can be regarded as a simple configuration with a generator as the major component. Other coupled systems may utilise the exhaust gas heat of the propulsion engine, which is preferable in terms of the overall efficiency but not commonly used for the small power range (e.g., automobile). Exhaust gas conversion with steam turbines in large ships or thermoelectric generators are rare examples of such configuration. It is self-evident that coupled systems generate only power as long as the propulsion engine is operating. Hence propulsion engine idling for electricity generation can be common (e.g., trucks), but this is undesirable in terms of the fuel consumption and noise. Electrical storage

systems can only partly overcome idling. The secondary battery concept in the transport sector has disadvantages in terms of the energy density, self-discharge, low temperature performance and constant “key-off” load supply. For example in the automobile, “key-off” loads (e.g., keyless entry, theft alarm and clock) are sufficient to drain the battery in a state-of-the-art car when left parked for long periods (e.g., at an airport for several weeks) [130]. For some applications the security of electricity supply can be another concern. Systems coupled to a propulsion heat engine are susceptible to a propulsion engine failure. For all these reasons electricity generation decoupled (auxiliary) from the propulsion is of interest.

There are several technology options for auxiliary power units (APUs), such as reciprocating engine generators, fuel cells or direct heat-to-electricity devices. Transport applications with a large power requirement may apply for example gas turbines as APUs (e.g., aeroplane, ship). As already mentioned in the previous paragraph, smaller power applications typically rely on a propulsion engine coupled generation (e.g., automobile, trucks). This smaller power range, assumed here up to a power of 10 kW_{el}, has been identified as a potential market for TPV. TPV APUs could be also of interest down to very small powers in the order of watts to supply “key-off” loads in automotive applications [130]. This “key-off” power is small compared to the propulsion power and the operation time may be limited (e.g., to an airport visit), so that the importance of the efficiency can be regarded as secondary. Hence, a typical thermoelectric generator efficiency of 3% has been assumed as a lower limit.

The *technology constraints* and the research and development effort have been assessed as balanced. The MIT together with a car consortium considered TPV APUs [131]. Another positive aspect is seen here in the low efficiency requirements (fuel on-site) for the small powers. The major challenge is seen in the harsh operation environment (e.g., automobile with a wide temperature and humidity range, as well as vibrations). Fuel cells are identified as one major emerging *competitor*. It can be assumed that TPV advantages, and in particular the flexible operation on any propulsion fuel, outweigh the high efficiency of fuel cells. In the small power range there is some competition from deployed niche market thermoelectric generators, but these systems have a low efficiency. Hence, TPV should have advantages over deployed and emerging technologies. *Market and cost* issues have been rated balanced. In general there is a market requirement for reliable APUs. The automotive market is a large potential market [130] and niche markets are also feasible (e.g., TPV generator working in CHP mode for truck idling). On the other hand, public funding is regarded as less likely. In general hybrid vehicles are more likely to be funded due to their energy saving potential. The local *human impact* has been rated as positive, because local pollution, noise, security of supply and user friendliness can be expected to improve. The global human impact was rated negative, since no major primary energy saving can be expected.

8.4.6 Combustion Application: Combined Heat and Power

Combined heat and power (CHP), also known as cogeneration or total energy, is the simultaneous generation of heat and electricity [132, 133]. Mechanical and cooling power is not considered here further, although it may be also defined as CHP. CHP is an attractive energy saving option because of its high overall efficiency (typically 80–90%) defined as the ratio of useful heat and electricity output to the fuel energy input. This efficiency value can be compared with the low efficiency of centralised fossil fuel power stations that release huge amounts of waste heat to the environment. Cost effective operation of CHP systems typically requires a runtime of several thousand hours per year and decisive economic factors are the capital cost of the CHP system, as well as the fuel and electricity prices [134].

The generated heat varies from low-grade (e.g., hot air or water for space heating) to high-grade (e.g., steam for industrial applications). TPV systems are currently limited to low-grade heat generation, because the heat originates from the PV cell cooling. TPV systems operating with cell temperatures up to about 90°C have been reported [135], but a typical cell temperature may be currently around 60°C in CHP mode. Generally, remaining flue gas heat leaving the TPV system using an additional heat exchanger could upgrade this heat [8, 9]. Hence, overall efficiencies higher than the assumed 80% of this assessment and higher heat supply temperatures than 60°C are regarded as feasible in future.

CHP systems tend to be built on-site and matched to the heat load, because transportation of heat over long distances is usually difficult. Short-term time-varying heat demand can be bridged by thermal energy storage systems. Below 100°C water is a simple and effective thermal energy storage media. Water can also act as the heat carrier media (no heat exchanger required), is widely available and has one of the highest sensible heat contents of any liquid around ambient temperatures [136]. In CHP systems the PV cells are usually cooled by water and the sensible heat of the water can be stored in tanks as in some conventional central heating systems. Long-term variation of the demand does usually not allow matching of supply and demand in all cases. This situation can lead to a larger sized and shorter operating CHP system. A known example is the space heating demand with seasonal variations using an oversized system in the summer. The electricity output tends to be less critical compared to the heat output, since electricity can be consumed on-site and surplus electricity can be exported to the grid. Electrical output powers of traditional CHP plants typically range from 100 kW to 100 MW using primary movers such as steam turbines, gas turbines or reciprocating engines combined with a generator [132]. Recently, several emerging technologies allow smaller-sized systems with electrical output powers as small as around 1 kW. The smallest systems have been named micro CHP [134, 137, 138].

Table 8.4 summarises the reported CHP TPV research in literature. The table lists the research and development status, the PV cell material, the thermal

Table 8.4 CHP TPV developments by different institutions

Application	Institution	R & D status	PV cells	Output power	Efficiency target	Source
Micro CHP	JX-Crystals, US WS GmbH, Germany	Partly built	GaSb	1.5 kW_{el} 12.2 kW_{th}	$\eta_{el} = 12\%$ $\eta_{sys} = 80\%$	[78, 110]
Self-powered heating (Midnight Sun®)	JX-Crystals, US	Beta testing of 20 units	GaSb	7.3 $kW_{th\#}$ 0.1 kW_{el}	$\eta_{el} \sim 1–2\%$	[24, 139]
District and industrial heating	JX-Crystals, US	Partly built	GaSb	147 $kW_{th\#}$ 20 $kW_{el\#}$	$\eta_{el} \sim 10–15\%$	[77, 140]
Self-powered heating	Quantum Group, US	Demonstrated	Si	0.2 kW_{el} 19.2 $kW_{th\#}$	$\eta_{el} \sim 1\%_{\#}$ $\eta_{sys} > 83\%$	[141]
Self-powered heating, Micro CHP	PSI, Hovalwerk AG	Partly built	Si	0.2–1.5 kW_{el} 10–20 kW_{th}	$\eta_{el} = 1–5\%$	[85]
Micro CHP	ISE, Freiburg	Partly built	GaSb	0.13 $kW_{el\#}$ 1.1 $kW_{th\#}$	$\eta_{el} = 7\%$ $\eta_{sys} = 60\%$	[142]
Back-up, Micro CHP	ISET, Kassel	Demonstrated	GaSb	60 W_{el} 1.2 $kW_{th\#}$	$\eta_{el} = 4\%$ $\eta_{sys} = 86\%$	[143]
Micro CHP	Dutch Energy Research Found.	N/A	Si	N/A	N/A	[144]
CHP	British Gas Research & Techn. Centre	N/A	N/A	0.3 kW_{el}	N/A	[144]
Micro CHP, District heating	SERC, Sweden	Partly built	InGaAs GaSb	10–1,000 kW_{th}	N/A	[93]

and electrical output power, the efficiency and the literature sources. Efficiency and power values marked with # have been calculated in this work.

In the presented assessment three application groups were identified. These are self-powered heating devices (discussed in Sect. 8.5.2) and two CHP applications with different power levels: micro CHP (small power), district heating and industrial CHP (large power).

Micro CHP systems aim to replace conventional boilers in a dwelling and provide both electricity and heating to a single-family house. To make CHP suitable as a boiler replacement the size of traditional CHP systems needs to be reduced. There are requirements in terms of high reliability, low local pollution, low noise and low costs [134, 145]. Both US and European studies have identified an efficiency target from fuel-to-electricity in the range from 10 to 25% and an overall efficiency target of 80% or higher [134, 145]. The 10% electrical efficiency has been adopted as a minimum target in this assessment. Generally, no deployed technology can fulfil all these requirements. At the moment, there are several technologies under active investigation for micro CHP systems each with their own drawbacks and strengths. At the time of writing, these small sized CHP systems are still in a development and demonstration phase [146].

Reciprocating internal combustion engine (ICE) systems have been traditionally the CHP systems with the smallest output power among the traditional CHP technologies. Adapted reciprocating engine generators are under development to improve noise, local pollution and maintenance. Some systems with 5 kW_{el} output power are commercially available in Europe and smaller systems seem to emerge. Typical thermal efficiencies of small sized ICEs are 60% and electrical efficiencies are around 25% based on the lower calorific value of the fuel [146]. Small *Stirling engine* systems have become commercially available or are being developed. Stirling engines can have the advantage of a cleaner and more fuel flexible combustion compared to reciprocating ICEs. The electrical efficiency drops from large units ($\sim$30%, 50 kW) to small micro CHP units ($\sim$10%, 1 kW). *Rankine* systems with an electrical power of 1 KW to a few KW are also emerging from research and development laboratories [145]. Traditionally steam turbines have been mainly used for large-scale centralised power generation. For micro CHP, the working fluid water/steam is replaced by an organic fluid (Organic Rankine Cycle ORC). Generally the advantages are similar to Stirling systems (both are external heat engines). Rankine systems for micro CHP are considered to be in a less developed stage compared to Stirling systems and small systems show similar electrical efficiencies ($\sim$10%). At the moment, there are two major *fuel cell* types considered for micro CHP. These are SPFC and SOFC (see Sect. 7.3.2) [145]. Both types operate in field trials. The major advantage of fuel cells compared to other micro CHP technologies is the high electrical efficiency (30–40%). The major drawbacks have been identified to be capital cost, overall efficiency (e.g., for SPFC) and lifetime [146, 147]. *AMTEC* micro CHP systems have also been proposed [20]. *Thermoelectric* systems have also been considered for systems with a low electrical efficiency (self-powered operation) [70]. Future advances in thermoelectric system efficiency may also allow micro CHP operation.

For micro CHP-HTPV systems a target *power range* from 1 to 10 kW has been identified from the reviewed competing systems. A typical TPV system may aim for a power output of around 1 kW with stronger competition from other technologies in the power range close to 10 kW [9].

No major *technology constraints* could be identified. There have been developments towards prototypes by more than one institution and system performances could be partly demonstrated. The inverter and grid connection issues have been assessed for solar PV systems previously and have also been demonstrated for TPV operation [148].

There are no fully deployed *competing* technologies for micro CHP, but several emerging technologies as discussed previously. At the moment these are mainly ICE, Stirling, ORC, SPFC and SOFC systems [146]. The long-term strength of TPV is thought to be the solid-state operation. This should allow building micro CHP systems with the same maintenance requirements and reliability performance as existing boilers. The long-term energy efficiency of buildings is likely to improve, so that smaller-sized systems would be required. However, heat engine efficiencies tend to decrease for smaller sizes and scaling to various sizes could be also simpler for a TPV system. Fuel cells are also solid-state devices, have demonstrated high efficiencies and can be flexibly scaled. Nevertheless, even if all current fuel cell problems for micro CHP could be overcome (e.g., lifetime, economics), there could be still a long-term market for oil and biomass based micro CHP-TPV systems, since the fuel flexibility is another challenge of fuel cells. This discussion points out that there are specific TPV benefits over emerging competitors. On the other hand, there are a number of emerging technologies and they are close to the market. This is considered to outweigh specific TPV advantages. Hence, overall TPV has been not rated advantageous over its emerging competitors.

There is a huge mass *market* for micro CHP. For example, Great Britain and Germany have a huge gas boiler market that would be potentially suitable for micro CHP [138]. Important market aspects include a high total dwelling stock with central heating, a extensive natural gas distribution network, high annual boiler sales, liberalised gas and electricity market, suitable heating loads and suitable regulation to facilitate the connection of embedded generation [134]. There are also niche markets for non-grid connected systems and self-powered boilers allowing for higher capital costs. Funding is generally feasible, since the promise of primary energy saving has stimulated political interest (e.g., in the EU). TPV cost estimations indicate that TPV could compete with fuel cells and heat engines [85]. Hence, market and cost issues have been rated as positive.

The *human* impact has been identified as very positive (rating 3). Micro CHP has the potential of considerable primary energy savings, if large numbers of central heating boilers could be replaced [134]. The slight increase in local energy consumption (or local pollution) of a micro CHP system compared to current conventional boilers is not seen as a major disadvantage. In long-term micro CHP systems promise cost savings with a slight increase of fuel costs but major savings in electricity costs for the user. Micro CHP is also a potential technology for grid-independent backup power in case of a power failure.

In addition to micro CHP (1–10 kW) there has also been interest in larger sized TPV systems. TPV systems with thermal powers of over 100 kW and even up to 1,000 kW for apartment, *district and industrial heating* have been proposed [77, 93, 140]. This results in an electrical *power range* from about 10 to 100 kW assuming the same *efficiency* range as for micro CHP (10–15%). Scaling-up of the TPV output power has not been demonstrated yet. However, TPV systems can operate modular as proposed by Fraas et al. [77], so that *technology constraints* similar to those for micro CHP can be expected. *Competition* arises from both deployed and emerging technologies. Deployed reciprocating ICE CHP systems are commercially available. Maintenance and noise of these engines have been regarded as acceptable for the large CHP range compared to micro CHP systems (e.g., installation in a separate room may be common). Small gas turbines, known as micro-turbines, are an emerging technology. The Stirling engine with an output power of tens of kWs is another emerging technology [149]. It is concluded that there is strong competition from both deployed and emerging technologies and no clear overall benefit could be identified using TPV (Rating 1).

Promising niche *markets* are applications with a steady heat demand over the course of a year. Examples are swimming pools, leisure centres or industrial heat processes [150]. There has been some cooperative research of the industry and a TPV company (ABB with JX-Crystals). The feasibility of primary energy saving should allow funding. In terms of capital system costs per output power, it needs to be considered that ICE systems become increasingly cheaper for larger output powers. TPV systems are likely to be mainly determined by PV cell costs. Hence, TPV system costs per output power can be expected relatively constant for increased output powers. One positive aspect is that industrial and distributed heating CHP systems could have longer operation hours to improve economics compared to micro CHP systems. Overall the market and cost indicator has been rated balanced. It has been assumed that there are generally suitable market conditions, but some cost constraints. Similar considerations have been made for the *human impact* as for micro CHP.

8.5 Waste Heat Recovery Generator

8.5.1 Waste Heat Source

Waste heat applications are defined in this work as those where the major purpose is heat rather than electricity generation. In such applications TPV systems can converts a small share of the waste heat into electricity. Applications using waste heat sources have the advantage of the availability of free or low cost heat. In some cases this heat is accessible without interruption, such as for industrial high-temperature processes operating throughout day and night. Finally the efficiency is often not a decisive factor in these applications where heat is generated in any

case. Two applications are identified. These are self-powered heating (Sect. 8.5.2) and industrial waste heat recovery (Sect. 8.5.3).

8.5.2 Waste Heat Application: Self-Powered Heating

Self-powered heating is of interest where operation during power faults is critical or no public electricity grid is available. The end-use of the hydrocarbon based combustion heat includes applications such as for space heating, hot water and drying. Examples are self-powered central heating units, district heating units, space heaters with fans, portable heaters, tent heaters, independent vehicle heaters or self-powered furnaces [3, 4, 18, 20, 139]. For example modern central heating units cannot generate heat, if the public electricity grid fails. Hence, a self-powered operation independent of the public electricity grid is of interest. TPV work in the electrical power range from 10 W to 10 kW has been reported. Applications included a combined camping heater and generator [151], an off-grid stove [139], self-powered central heating units [85, 141] and heating units for apartment building [77, 140, 152]. Similarly, critical industrial heating processes may have additional backup power systems in order to ensure the operation during power faults. Also here, self-powered operation of industrial processes using a TPV heat recovery system would be advantageous.

Typically the heating devices have a much larger thermal power compared to the electrical power requirements. The end-use of the electricity is typically for control and heat distribution. Usually heat is distributed by forced convection (e.g., pumps, fans). The smallest thermal power has been assumed to be around 1 kW and this value corresponds roughly to the thermal power of a hairdryer. District heating units with thermal powers up to 1 MW also could have a need for grid-independent operation and have been assumed as an upper power range limit. From different sources [85, 139, 141] it becomes clear that these devices typically have an electricity requirement in the order of 1% of their total heat consumption. Consequently an electrical power range from 10 W to 10 kW has been calculated from the thermal range.

Lower electrical powers than 10 W are also feasible. Work by Goldstein and DeShazer [153–155] and the author [156] demonstrated that radiation could be extracted from a process by thermally stable dielectric solid radiation guides (see Sect. 6.3.4). In this arrangement one side of the dielectric solid light guide is in the high-temperature heat source environment, where radiation is coupled into the guide, and the other end can have a low temperature and illuminates the PV cell. Using total internal reflection allows radiation guidance. For example, thermoelectric generators typically utilise conduction to transfer heat to the thermoelectric modules. Thermal conduction can be associated with temperature gradients. Hence, thermoelectric modules need to be placed close to the heat source in order to achieve high hot side temperatures. On the other hand, an optical guide can transfer radiation with little losses over long distances. It can be assumed

that the radiation guide is simpler than other TPV systems using a cavity with challenging high-temperature mirror design. The light guide arrangement could be inserted into any high-temperature process with a suitable temperature. It seems likely that such arrangement could be also used to convert small amounts of (waste) heat into electricity. Feasible applications include self-powered heating devices (e.g., powering of displays or thermostats), self-powered sensors and fire energy converters for camping. Goldstein also proposed the conversion of jet engine heat into electricity using dielectric solid light guides [154].

The variety of potential applications and technological options results in a wide *power range*, which has been assumed from mW to 10 kW. Similarly, efficiency requirements in a wide range can be expected. A marginal *efficiency* would be sufficient to power a small sensor (e.g., 10 mW electrical from 10 W thermal). On the other hand, a self-power high-temperature process may have high efficiency requirements. For example a high-temperature process with a power of 1 MW_{th} could require 1% of its thermal input as electricity (10 kW_{el}). Assuming a TPV efficiency $\eta_{TPV} = 13\%$ results in 67 kW_{th} low-grade heat. Such low-grade heat may or may not be utilised. Such generator would extract 77 kW_{th} or about 8% of the total thermal power as heat. The example shows that, unless there is a need of low-grade heat, the efficiency of the TPV generator for self-powered operation of high-temperature processes should be high. Nevertheless the extraction of 8% of the total heat input seems feasible and the maximum efficiency target was set to the near-term value of 13%. If low grade heat can be utilised, such as for space heating, the TPV efficiency requirements can be much lower. For example, a self-powered central heating unit with 20 kW_{th} could deliver 10 kW_{th} to the TPV system. The TPV system could convert 2% of this heat into 200 W_{el} or 1% of the total heat input. The 9.8 kW_{th} low-grade heat from the PV cells may either be used directly or upgraded by the remaining 10 kW_{th}.

The *technology constraints* and the research and development effort have been rated as positive. Positive factors were the (partly) low efficiency requirements (partly) simple overall design (e.g., sensor powered by light guides) and beta tests of the Midnight Sun® oven [139]. *Competing* deployed technologies are not available in this niche market. There is some experience with self-powered heating systems using thermoelectric generators [157]. Thermoelectric generators are limited in terms of efficiency. It is currently challenging to design a thermoelectric generator with more than 3% efficiency [17]. Hence, TPV conversion is seen superior over its competitors in this configuration. The *market and cost* indicator has been rated as positive. Self-powered heating devices are used in niche markets, where higher system capital costs could be justified. In long-term this application could grow into the large micro CHP and industrial waste heat recovery market. The US Gas Research Institute identified self-powered devices as the major future market for TPV [4] and there is general interest in the TPV community for this application (e.g., Midnight Sun® system). Hence, market and cost issues have been rated as positive. TPV could improve security of electricity supply during power faults. This resulted in a positive local *human impact* rating. The total energy

consumption is largely unaffected for the small share of electricity generated (negative global human impact factor).

8.5.3 Waste Heat Application: Industrial High-Temperature Processes

In the large power range, the recovery of *industrial high-temperature waste heat* by a TPV system has been proposed by Coutts [158]. One major attraction of industrial waste heat recovery is that the heat is freely and often steadily available and that the electricity generated can be typically used at the industrial site. The low-grade heat generated by the TPV system may also be utilised for space heating if a demand can be identified. The potential industries for high-temperature waste heat recovery include the iron and steel, non-ferrous, bricks, refractories, cement, ceramics and glass sectors. In particular the glass industry has been suggested [140, 152]. An US company (JX-Crystals) received funding from the US Department of Energy and the company partly developed TPV generator tubes each with an output power of 5 kW_{el} [77, 140, 152]. These tubes could be inserted in high-temperature processes in order to generate electricity and low-grade heat in the form of hot water. Two applications have been proposed, which are high-temperature waste heat recovery in the manufacturing industry and CHP supply for apartment buildings [77, 152]. Yamaguchi et al. [8, 9] assessed the potential of waste heat recovery in Japan. They found that waste heat recovery from flue gas for large industrial processes is already utilised for large furnaces using steam turbines based systems and hence they concentrated on small furnaces where they found temperatures to be too low for TPV operation. However, it was pointed out, that it is possible to upgrade small-scale flue gas heat using premium heat produced by an additional combustion process. Heat recovery from other locations than the flue gas was not considered in their work [8, 9]. The potential of TPV for heat recovery in the high-temperature industry in the UK was assessed by the author [159]. It was found that an overall assessment of TPV in those industries is complex mainly because of the large process diversity and because an individual assessment for each process in terms of TPV use is required. Hence, one example process for each of the three principal locations for heat losses has been assessed in detail. The principal locations and specific processes were product heat recovery on a continuous curved caster, flue gas heat recovery on a regenerative glass tank furnace and wall heat recovery on a 3-phase alternating current electric arc furnace.

Nearly all of the high-temperature processes coincide with a general type of process (Fig. 8.5). The energy entering the process chamber derives from electrical heating, combustion, a hot feedstock, or any combination of the previous sources. Within the process chamber the temperature exceeds 1,000°C. The combustion and feedstock/product may sometimes show interactions. Examples are the

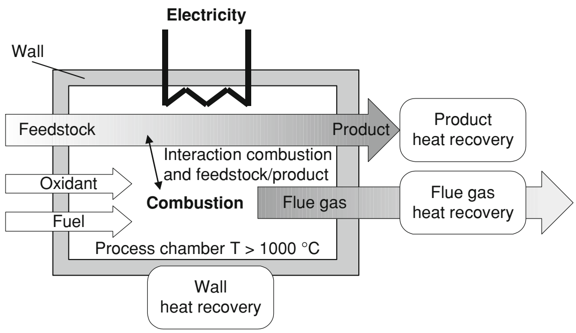


Fig. 8.5 Schematic of a general type of industrial high-temperature process

formation of CO_2 from glass forming reactions and the use of coke in a blast furnace as feedstock and fuel. The feedstock can be charged in different modes including batch, tap and charge or continuous type. The feedstock can consist of raw materials, recycled products or a mixture of both. Typically the specific energy consumption (SEC) of processes using recycled products is lower if compared with raw material processes. The important parameters to specify an industrial high-temperature process are the process temperature and pressure, fuel requirements, insulation losses and thermal efficiency, as well as the flow of mass and energy in the process [160]. The energy flow can be visualised in a Sankey diagram. Hence, this diagram can be used to identify major heat losses for possible heat recovery locations.

For the general type of high-temperature process considered (Fig. 8.5), there are three principal locations for heat recovery, namely product (1), flue gas (2) and wall heat recovery (3). Existing heat recovery methods most commonly utilise the flue gas location (e.g., glass furnace regenerators, pig iron blast furnaces) followed by the product and by-product (e.g., cement clinker cooler, blast furnace slag recovery [161]).

TPV systems could also utilise the sensible and latent heat of products and by-products. Other recovery technologies already utilise the calorific value of by-products. Examples are coke oven, blast furnace and basic oxygen furnace gases in the steel industry [162]. Insulation heat losses are rarely recovered and a rare example is the recovery of radiation losses from a shell of a cement rotary kiln [162].

Once potential sources of waste heat are identified, the end-use of the recovered energy needs to be considered. The use of the recovered energy in the same process (e.g., combustion air pre-heating, feedstock preheating) has several advantages, such as minimising the process SEC, avoiding long distance transport of heat and usually temporal matching of energy supply and demand [163]. However, the use of waste heat within the process is not always feasible and therefore this heat is available for external use (e.g., space heating, electricity generation). External use of energy may be classified by the type of energy conversion: heat-to-heat (e.g., steam or hot water production), heat-to-chemical energy (e.g., forming methane from blast furnace slag) or heat-to-electricity. Heat-to-heat conversion, mostly associated with heat exchangers has simplicity,

but is limited to applications where heat recovery and demand coincide since heat can only be transported to a limited extent. Additionally, heat exchangers may have problems with leaks, low efficiencies and fouling from flue gas, especially for temperatures higher than 1,000°C [163, 164]. Heat recovery technologies that generate electricity offer more flexibility since electricity can be transmitted with lower losses than for heat and electricity can be converted to other energy forms at high conversion efficiencies.

For thermoelectric systems it has been pointed out that a low *efficiency* is not a serious drawback in the conversion of free waste heat and that the capital cost per watt is the decisive economic factor [164]. These considerations can also be brought forward for TPV and thus the lower efficiency target range has been assumed with the demonstrated efficiency (6% for non-combustion systems).

The use of 200 tubes each with 5 kW has been suggested in a glass furnace [152]. This would result in an electricity output *power* of 1 MW. This value has been assumed as an upper power range limit for this assessment. Small high-temperature furnaces could also have a requirement for self-powered operation, which would result in a minimum electrical power of 1 kW assuming 1% of a 100 kW thermal furnace.

A partly demonstrated TPV system indicates that there should be no major *technology constraints* [77]. Also a TPV heat recovery system does not require the design of an efficient combustion unit. This should result in a simpler system design. The integration of a TPV system in an industrial process requires some further consideration (e.g., adaptation to process temperature levels and temporal variations). Hence, a balanced rating has been given for the technology constraints and research and development effort.

Competing technologies are external heat engines and direct heat-to-electricity converters. External heat engine based systems operate with different thermodynamic cycles, such as the Rankine or Stirling cycle. These cycles can use different working fluids and may be of open or closed type. This results in a variety of potential recovery systems using external heat engines [165, 166]. For high-temperature waste heat sources of interest here (above 1,000°C), the inlet temperature at the heat engine is usually lower than 1,000°C. There may be different reasons for this including high-temperature engineering difficulties and deliberate cooling for the conversion (e.g., because the heat engine operates at a lower inlet temperature). Also, typically the heat needs to be piped to the heat engine, which inevitably leads to some collection and piping heat losses with heat degradation. One deployed competing combination of technologies generates electricity from heat in the flue gas. This combination consists of a heat exchanger, a high-pressure steam boiler, a condensing steam turbine and a generator [163, 165]. However, the complexity of this approach associated with high capital and maintenance costs limits applications to large industrial plants using only the flue gas heat. On the other hand, TPV systems could be scaled in a wide power range. Also, TPV systems could not only recover flue gas heat, but such system could also convert heat of hot products leaving the process and heat lost through walls. Emerging competing technologies include heat engine concepts based on the organic

Rankine [166], the Stirling [167] and the air-bottoming cycle [165]. Heat engines are usually limited to the conversion of flue gas heat. Product and wall heat losses are typically not converted into electricity using external heat engines.

Direct heat-to-electricity conversion devices have advantages in terms of low maintenance, high reliability, good scalability and low complexity compared to heat engines. In addition, they could be used directly at any heat source (flue gas, wall, product) so that collection and piping losses could be avoided. The major direct heat-to-electricity conversion devices currently of research interest are thermoelectric generators [164, 168]. However, these generators can commonly convert only low-grade heat with hot side temperatures of around 400 K or lower temperatures [164, 168, 169]. High-temperature thermoelectric generators are feasible but there are still engineering challenges to be overcome (Sect. 7.4.1). For high-temperature thermoelectric generators, sufficient and reliable electrical contacts and mechanical properties are difficult to achieve [169]. Hence, thermoelectrics could recover low-temperature heat (<400 K) and TPV the high-temperature heat (>1,300 K). Advances in both technologies may allow the entire temperature range to be covered using direct energy conversion devices. Hence, it can be argued that thermoelectric and TPV generators are not competing with each other, but they should be seen as complementary.

For example, classified by type of use, high-temperature processes accounted for about one quarter of the industrial energy consumption in the UK in 1999. High-temperature processes can be further classified by sector. Most of these sectors have energy-intensive processes operating at temperatures above 1,300 K and which are suitable for TPV operation [160]. This shows that there is a large *market* for industrial waste heat recovery. Niche markets could be self-powered furnaces and backup power supplies in the industry. Funding has been available in the US [152] and very long operation hours should keep payback periods low. From these considerations a positive market and cost rating has been given. The local and global *human impact* has been rated as positive. Primary energy savings are feasible and no additional pollution due to TPV operation should occur. Electricity generation by TPV would be expected to require low maintenance. On-site use of electricity is another environmental advantage.

8.6 Summary

The assessment has been an iterative process, which considered the availability of different heat sources, the capabilities of TPV and competing conversion technologies, as well as the application requirements. The applications have been classified by heat source and CHP mode. Table 8.5 gives the final result of the assessment. Figure of merit ranges for both efficiency and electrical power output of each application have been identified. The four indicator groups have been rated from 1 to 3. The applications with the highest potential were identified by summing these indicators for each application (Table 8.5). It is in the nature of such

Table 8.5 Potential TPV application classified by heat source and CHP mode. For each application figures of merit for the electrical efficiency and power range have been identified. The four indicators are summed up to the final result

	Figure of merit ranges		R & D Effort	Competit. & benefit	Market & cost	Human impact	Final result
	Electrical efficiency (%)	Electrical power					
Combustion non-CHP							
Portable generator	5–15	1 W to 1 kW	2	3	3	2	10
Uninterruptible power supply	5–15	100 W to 10 kW	1	2	2	2	9
Unmanned remote power	3–15	1 W to 1 kW	1	2	2	1	6
Remote renewable hybrid system	5–15	100 W to 10 kW	1	2	2	3	8
Small vehicle propulsion	15–20	100 W to 10 kW	1	3	1	2	7
Vehicle auxiliary power units	2–15	1 W to 10 kW	2	3	2	2	9
Combustion—CHP							
Micro CHP	10–15	1 kW to 10 kW	3	2	3	3	11
District/industrial CHP	10–15	10 kW to 100 kW	3	1	2	3	9
Solar							
Solar TPV storage/combustion	13–25	100 W to 10 kW	1	3	3	3	10
Nuclear							
Space radioisotope generator	19–25	10 W to 1 kW	1	3	3	1	8
Waste heat							
Self-powered heating devices	<13	1 mW to 10 kW	3	3	3	2	11
Industrial waste heat recovery	6–19	1 kW to 1 MW	2	3	3	3	11

assessments that the assumptions have a decisive impact on the results. In general, it can be pointed out that TPV systems could be potentially utilised in all of the twelve identified application fields. The human impact considers the following factors: primary energy savings, low NO_x, low noise, improvement of the security of supply and user friendliness.

Hydrocarbon fuels are widely available, can be easily stored, transported or refuelled, and have high energy density. Combining fuel properties and TPV technology capabilities results in several potential applications. Competing technologies for these applications are mostly batteries in the smaller power range and internal combustion generators in the larger power range. Here, fuel cells are seen as the major future competitor. Portable power applications have been identified as most promising in this group. Military interest and another TPV assessment for Japan also indicate the potential. APUs operating independently of the vehicle propulsion have had less attention in the TPV community, but are regarded here as an application field with a high potential. In particular, applications with low noise, high reliability or low complexity requirements should hold promise.

In CHP systems both heat and the electricity output are utilised. Micro CHP systems aim to replace conventional boilers in a dwelling and have been identified as one of the most suitable TPV application of this assessment. In Western Europe and the US there is some major interest in micro CHP. Generally TPV technology capabilities match the micro CHP requirements, namely high reliability, low maintenance and low noise. Currently, there are several other emerging technologies with similar capabilities operating in field trials and this competition can be regarded as one major challenge for TPV developments. Industrial and distributed CHP systems could have longer operation hours to improve economics and have also been identified as a promising.

At the current stage, *solar* concentrator PV systems outperforms solar TPV systems in terms of efficiency. It is concluded here that even if solar TPV systems could not demonstrate their potentially high efficiency, such systems would have still some unique advantages. Solar TPV systems can use a thermal storage or additional hydrocarbon combustion to bridge solar fluctuations and ensure a flexible and reliable supply of electricity. CHP operation and biomass utilisation of such systems is also feasible. In particular smaller autonomous operating systems without an electrical grid could be of interest.

Space power for near sun and deep space missions is a niche market for *radioisotope* generators. TPV generators could meet the requirements of this high value niche market with unique advantages in terms of lifetime, power density and efficiency compared to other technologies (e.g., TE, Stirling and AMTEC).

Self-powered heating can be considered as an ideal near-term market. Particularly suitable applications are those with a requirement of low-grade heat such as for space heating. This results in low efficiency requirements that have been demonstrated. In long-term, this niche market could grow in larger primary energy saving markets such as industrial waste heat recovery and micro CHP. TPV *high-temperature industrial waste heat recovery* has been also identified as a very suitable application. Potential advantages are primary energy savings, high

operation time, low competition from other technologies and moderate efficiency requirements due to the free or low cost of the thermal input. Also, many high-temperature processes are susceptible to power failures, where TPV could act as a backup power source. This high value backup market could be used to launch the TPV heat recovery systems.

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